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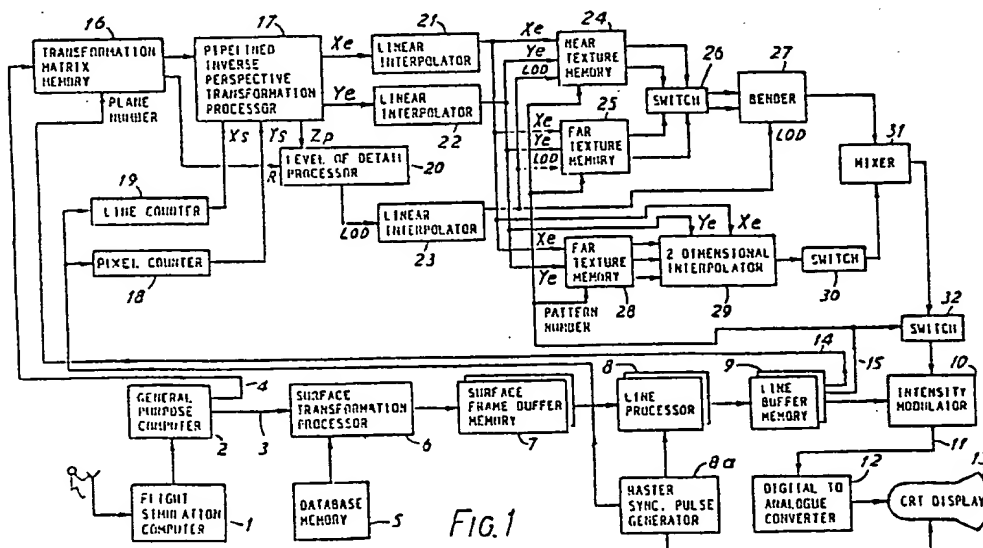(51) INT CL⁴
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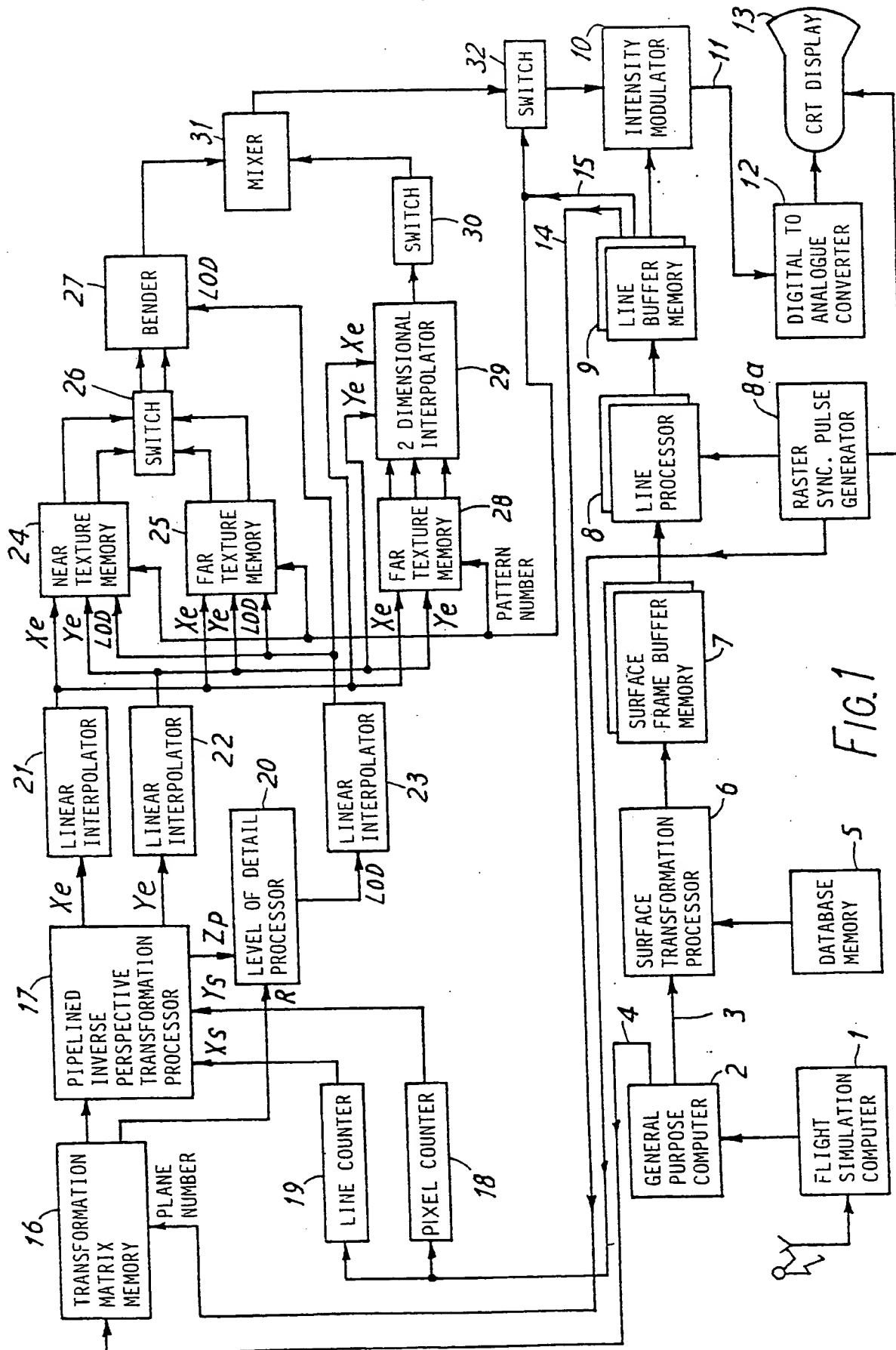H4T 4R BRC
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(56) Documents cited
GB A 2138252   GB A 2051525
GB A 2061074   GB A 2019336

(58) Field of search
H4T
Selected US specifications from IPC sub-classes G09B
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(54) **Apparatus for generating a visual display**

(57) A flight simulator has a flight simulation computer 1 to which a computer generated image apparatus is connected to provide a visual display on a CRT display 13 for a trainee pilot. Flight position and attitude data generated by the simulation computer 1 is supplied to the GGI general purpose computer 2. Digital data for surface vertices are stored in a database memory 5 together with codes for overall intensity, texture pattern and surface plane. A surface transformation processor 6 generates a perspective transformation of viewable surface vertices and supplied raster line surface start and end points to a surface frame buffer memory 7. A line processor 8 writes corresponding pixel data into a line buffer memory 9. The intensity data is modulated in an intensity modulator unit 10 before D to A conversion for the CRT display 13. Position and attitude data is supplied by the general purpose computer 2 to a texture generator having an inverse perspective transformation matrix memory 16 for such data, a pipelined inverse perspective transformation processor 17 which utilizes such data and screen pixel coordinates X_s and Y_s to generate texture memory plane coordinates Xe and Ye and a level of detail signal LOD to be applied to address a near texture memory 24 and a far texture memory 28, or a far texture memory 25 alone. Intensity modulation values are thus obtained and supplied to the intensity modulator unit 10 to modulate the pixel intensity data for pixels in textured surfaces.
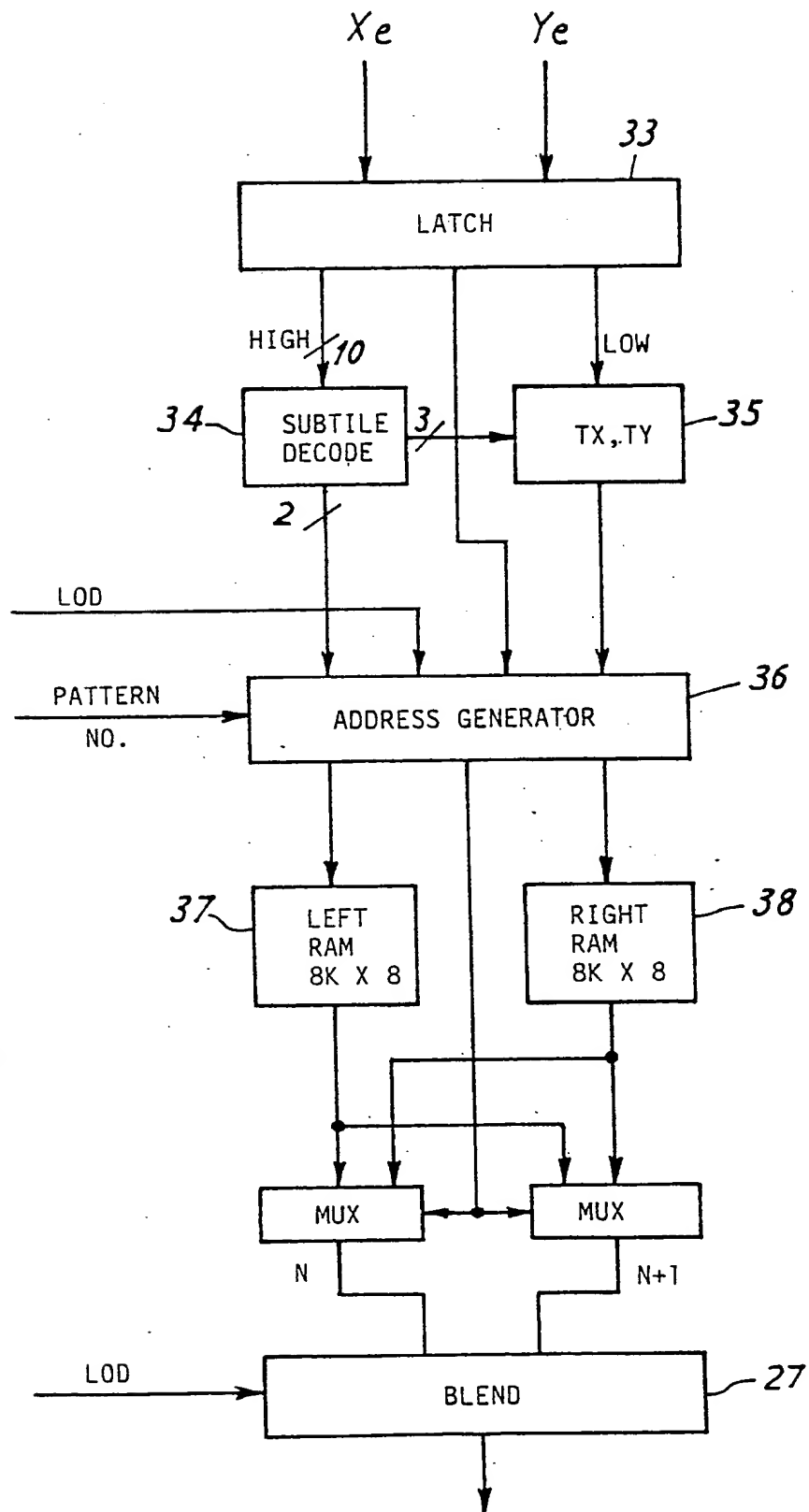

FIG. 1

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The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

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FIG.1

FIG.2

SPECIFICATION
Apparatus for Generating a Visual Display

This invention relates to apparatus for generating a visual display, and especially to computer
generated image apparatus.

5   Various techniques and apparatus for computer generated images are discussed in "Computer Image   5
Generation", edited by Bruce J. Schachter and published by John Wiley & Sons of New York in 1983, ISBN
0-471-87287-3.

One field in which computer image generation is being used is visual display systems for flight
simulation systems. A typical flight simulation system has a replica of a pilot's seat and aircraft controls and
10   instruments mounted on an enclosed platform which is moved to a limited extent to simulate changes in   10
attitude of an aircraft in response to use of the controls by a trainee pilot in the seat and accelerations
associated with changes of motion. A visual display is also mounted on the platform and presents the
trainee pilot with a simulation of the view to be expected for the simulated flight, such flights being based
on real possible journeys or flying conditions. The visual display may be presented by two or three display
15   devices arranged to simulate aircraft windows through which the pilot would see the outside world.   15

United Kingdom patent specification GB 2,019,336 describes a visual display apparatus for a
ground-based craft flight simulator comprising a raster scan type display device for viewing by a trainee
pilot, and a synthetic image generator which supplies the display device with a signal representing an
image of a sky, a horizon and a simulated cloud surface being overflown. This known apparatus has a digital
20   store holding a single pattern cycle of a repetitive pattern which is used to create the cloud pattern effect in   20
one dimension. In another United Kingdom patent specification, GB 2061074, an apparatus is described
which is intended to be combined with a polygon-based raster scan image generator and produces a signal
for creating a so-called "textured" appearance in a displayed ground plane. A polygon-based raster scan
image generator is a known type of computer image generator that, by utilising the simulated attitude and
25   position data produced by a computer-controlled flight simulator, calculates the raster display coordinates   25
of the boundaries of surfaces in the simulated perspective view of territory or cloud being flown over, and
controls the intensity of the display so as to produce different assigned intensities, and usually colours, for
the different surfaces. The intensity of any particular surface simulated by a polygon-based raster scan
image generator acting alone is uniform over that surface, and consequently lacks the visual clues provided
30   in real situations by the surface detail of surfaces. A well known example of the visual clues given by surface   30
detail is the information given by the pattern formed by bricks in a brick wall. GB 2061074 describes a
surface detail generator which is intended to be used to modulate the intensity signal output by a
polygon-based raster scan image generator so as to create perspective transformed views of a single
pattern lying in the displayed ground plane only. Also, although GB 2061074 discusses a memory hierarchy
35   of the pattern stored in a plurality of levels of detail and the selection of an appropriate level of detail by   35
using the sample spacing computed in simulated ground distance from the effective sample spacing along
a raster line as a measure, GB 2061074 does not provide any technique for avoiding banding effects which
can result from the changeovers between successive levels of detail, and since a large plurality of levels of
detail are stored, the amount of memory required to store the pattern at all these levels is relatively large.
40   Furthermore, GB 2061074 does not disclose any means of associating particular surface detail effects with   40
particular surfaces defined by the output of the polygon-based raster scan image generator.

According to one aspect of the present invention there is provided apparatus for generating a visual
display, comprising
first memory means storing geometrical surface data and associated surface appearance data
45   including surface intensity data, the geometrical surface data including coordinates for points characteristic   45
of defined surfaces and plane identifying data associating each of one or more defined surfaces with a plane
definable within the coordinate system of the said points,
first processing means arranged to select from the data stored in the first memory means geometrical
surface data and the associated surface appearance data for creating a display of a restricted
50   two-dimensional perspective view of a region defined by observation point and attitude data supplied to the   50
first processing means, the first processing means including input means for receiving variable observation
point and attitude data,
display means coupled to the first processing means for displaying the said restricted perspective view,
second memory means storing surface detail data representing at least one planar pattern, the surface
55   detail data comprising a plurality of intensity modulation values each stored at an address defined by a pair   55
of pattern plane coordinates,
second processing means coupled to the input means to receive observation point and attitude data
and to means for generating and supplying thereto pairs of display coordinates corresponding to points in
the visual display, the second processing means being such as to generate for each pair of display
60   coordinates supplied thereto a corresponding pair of pattern plane coordinates substantially determined by   60
an inverse perspective projection from the observation point to a plane defined in the coordinate system of
the said points characteristic of defined surfaces, the first processing means including means for supplying
the said plane identifying data to the second processing means and the second processing means being
adapted to utilize a perspective transformation associated with the plane identifying data,

addressing means coupling the second processing means to the second memory means so as to address the second memory means with the pairs of pattern plane coordinates, and

intensity modulation means so coupling the second memory means to the display means as to cause the intensity data selected by the first processing means for a displayed point to be modulated by an
5 intensity modulation value obtained from the second memory means for the same displayed point. 5

This first aspect of the invention enables surface detail to be applied to selected surfaces visible in the display.

According to another aspect of the invention there is provided apparatus for generating a visual display, comprising
10 first memory means storing geometrical surface data and associated surface appearance data 10 including surface intensity data and surface detail pattern identifying data, the geometrical surface data including coordinates for points characteristic of defined surfaces,

first processing means arranged to select from the data stored in the first memory means geometrical data and the associated surface appearance data for creating a display of a restricted two-dimensional
15 perspective view of a region defined by observation point and attitude data supplied to the first processing 15 means, the first processing means including input means for receiving variable observation point and attitude data,

display means coupled to the first processing means for displaying the said restricted perspective view,

second memory means storing surface detail data representing a plurality of identifiable planar
20 patterns, the surface detail data for each pattern comprising a plurality of intensity modulation values each 20 stored at an address defined by a pair of pattern plane coordinates,

second processing means coupled to the input means to receive observation point and attitude data and to means for generating and supplying thereto pairs of display coordinates corresponding to points in the visual display, the second processing means being such as to generate for each pair of display
25 coordinates supplied thereto a corresponding pair of pattern plane coordinates substantially determined by 25 an inverse perspective projection from the observation point to a plane defined in the coordinate system of the said points characteristic of defined surfaces, the first processing means including means for supplying the said surface detail pattern identifying data to the second memory means,

addressing means coupling the second processing means to the second memory means so as to
30 address the second memory means with the pairs of pattern plane coordinates, the second memory means 30 being adapted to output the intensity modulation values associated with the said pairs of pattern plane coordinates in the pattern identified by the said surface detail pattern identifying data supplied thereto by the first processing means, and

intensity modulation means so coupling the second memory means to the display means as to cause
35 the intensity data selected by the first processing means for a displayed point to be modulated by an 35 intensity modulation value obtained from the second memory means for the same displayed point.

According to a further aspect of the invention there is provided apparatus for generating a visual display, comprising

first memory means storing geometrical surface data and associated surface appearance data
40 including surface intensity data, the geometrical surface data including coordinates for points characteristic 40 of defined surfaces,

first processing means arranged to select from the data stored in the first memory means geometrical surface data and the associated surface appearance data for creating a display of a restricted two-dimensional perspective view of a region defined by observation point and attitude data supplied to the
45 first processing means, the first processing means including input means for receiving variable observation 45 point and attitude data,

display means coupled to the first processing means for displaying the said restricted perspective view,

second memory means storing surface detail data representing at least one planar pattern at a plurality of levels of detail, the surface detail data comprising a plurality of intensity modulation values each stored
50 at an address defined by a pair of pattern plane coordinates, 50

second processing means coupled to the input means to receive observation point and attitude data and to means for generating and supplying thereto pairs of display coordinates corresponding to points in the visual display, the second processing means being such as to generate for each pair of display coordinates supplied thereto a corresponding pair of pattern plane coordinates substantially determined by
55 an inverse perspective projection from the observation point to a plane defined in the coordinate system of 55 the said points characteristic of defined surfaces, and to generate a level of detail signal representative of a measure of minimum spacing in the pattern plane at which a difference in appearance can be represented by the display means, the second processing means supplying the level of detail signal to the second memory means,
60 addressing means coupling the second processing means to the second memory means so as to 60 address the second memory means with the pairs of pattern plane coordinates at one or more levels of detail determined by the level of detail signal, and

intensity modulation means so coupling the second memory means to the display means as to cause the intensity data selected by the first processing means for a displayed point to be modulated by an
65 intensity modulation value obtained from the second memory means for the same displayed point, the 65

intensity modulation means including means for combining two or more intensity modulation values read out from two or more levels of detail in the second memory means in response to a respective pair of pattern plane coordinates so as to produce the said intensity modulation value which modulates the selected intensity data. The addressing means may be arranged to address the second memory means at
5 pairs of adjacent levels of detail and the intensity modulation means be such as to blend the values from the   5
said adjacent levels so as to prevent banding effects at the display means. The addressing means may be such as to transform the pairs of pattern plane coordinates in response to predetermined values of the level of detail signal so as to use the said pair of pattern plane coordinates to address a predetermined restricted area of the pattern plane relative to a plurality of different addressing schemes, whereby for the
10 predetermined values of the level of detail signal, the second memory means may store the respective   10
planar pattern in the form of one or more sub-units of the pattern.

The second processing means may include means for generating successive pairs of pattern plane coordinates by interpolation. Similarly, successive values of the level of detail signal may be generated by interpolation.
15   The said input means of the first processing means may include a general purpose computer adapted   15
to supply perspective transformation data for use by the first processing means and inverse perspective transformation data for use by the second processing means. The second processing means may include transformation data memory means for storing inverse transformation data supplied thereto by the general purpose computer and be adapted to select such stored data in dependence upon plane identifying data   20
20 supplied thereto by the first processing means.

The invention will now be described in more detail, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a block schematic diagram of an apparatus embodying the invention, and

Figure 2 is a block diagram of circuitry for implementing part of the embodiment of Figure 1.
25   In the Figure 1 of the drawings there is shown in a schematic block diagram a visual display processing   25
system for a flight simulator having a flight simulation computer 1 which serves as the host computer in relation to the visual display processing system.

The flight simulation computer 1 controls an enclosed platform (not shown) on which a trainee pilot is seated. The trainee pilot operates a replica of the controls of a particular aircraft and the computer 1, in
30 response to input signals developed by the replica controls, moves the platform in a manner which to some   30
extent produces the sensation of changes in attitude and movement of the simulated aircraft. The simulation computer 1 also generates data signals representative of the longitude, latitude, altitude and attitude of the aircraft corresponding to the position and attitude of the aircraft which would have resulted from the trainee pilot's operation of the replica controls. These position and attitude signals are supplied to   35
35 a general purpose computer 2 which is part of the visual display processing system.

The trainee pilot is presented with a visual display of the view associated with the current position and attitude on the screen of a cathode ray tube 13. The display is generated by a raster scan, and for each frame of the display, the general purpose computer 2 generates geometrical transformation matrix data signals 3 which it supplies to a surface transformation processor 6, and geometrical inverse transformation matrix   40
40 data signals 4 which it supplies to a transformation matrix memory 16.

A typical simulated flight is a flight from one airport to another. To provide a visual display corresponding to such a flight, the screen of the cathode ray tube 13 must show the pilot's view from take off at the first airport to landing at the second airport. The visual display processing system must be able to show correctly the view determined by any reasonably possible flight path. To limit the requirements, it is   45
45 typically arranged that the pilot can be presented with a view of the ground features and sky within a 100
mile radius of a reference point, known as the runway threshold, of each airport, the view between the airports outside these limits being restricted to flight above a cloud level, so that only sky and cloud features are then displayed. The geometric data for creating displays of the ground features and sky and cloud are held in a database memory 5 in the form of lists of coordinates for surface vertices, these coordinates being   50
50 referred to as earth coordinates and being given in three dimensions Xe, Ye and Ze to allow for the display
of buildings, other noticeably three dimensional features, and a cloud base. The geometric data for overflown cloud features is also held in the database memory in a similar form. The database memory 5 also holds data assigning a value for the intensity of each surface defined by a set of vertices, and texture data in the form of two codes, referred to as the pattern number for each defined surface which indicates the   55
55 texture effect to be displayed for the defined surface, and the texture plane number which identifies the type
of processing required in texture generation.

The earth coordinates for each airport have as their origin the respective runway threshold. The general purpose computer 2 is therefore arranged to supply to the surface transformation processor 6 a signal indicating the currently applicable earth coordinates origin, together with the transformation matrix data   60
60 signals which the processor 6 uses to transform the earth coordinates of each surface vertex read out from
the memory 5 within the earth coordinate system addressed into pilot coordinates Xp, Yp and Zp, the pilot coordinate system having the currently computed position of the pilot's eye as its origin and an angular relation to the earth coordinate system determined by the currently computed attitude, i.e. roll, pitch and yaw, of the aircraft. The complete list of sets of stored earth coordinates having as origin the runway   65
65 threshold indicated by the general purpose computer 2 is transformed by the processor 6 into pilot

coordinates. To select from the transformed coordinates those which will be used to determine the view displayed by the cathode ray tube 13, constants determined by the position of the pilot in the aircraft, the area of the window defined by the cathode ray tube 13 and the distance of the pilot's eye from the screen of the tube 13, are used by the processor 6 to reject surface vertices represented by pilot coordinates not falling within the square section pyramid defined by the pilot's eye and the window. The pilot coordinates of the remaining surface vertices are then transformed by the processor 6 into intermediate screen coordinates which have as their origin the centre point of the screen of the cathode ray tube 13.

The pilot coordinates, termed X_p, Y_p and Z_p, have the Z_p axis defined as the line from the pilot's eye through the centre of window and perpendicular to the plane of the window, the X_p coordinate being parallel to the width of the window, and the Y_p coordinate being parallel to the height of the window. The screen coordinates, termed X_s and Y_s are respectively parallel to the width of the window and parallel to the height of the window, both lying in the plane of the window. The window lies in the plane of the cathode ray tube screen and has the centre of the screen as its centre point. However, to compensate for a delay in the part of the processing system that produces texture signals, the height of the window is chosen to be greater than the height of the screen, the raster lines being scanned vertically.

The matrix data signals 3 generated by the computer 2 include representations of the aircraft position X_o, Y_o and Z_o in the applicable earth coordinate system, and a rotation matrix $[H]$ which defines the attitude of the aircraft. The processor 6 calculates pilot coordinates X_p, Y_p, Z_p for each set of earth coordinates X_e, Y_e, Z_e as follows:

$$\begin{matrix} X_p \\ Z_p \\ Y_p \end{matrix} = [H] \begin{bmatrix} X_e - X_o \\ Y_e - Y_o \\ Z_e - Z_o \end{bmatrix}$$

where

$$[H] = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}$$

$h_{11} = \cos\phi \cos\psi + \sin\phi \sin\theta \sin\psi$
$h_{12} = -\cos\phi \sin\psi + \sin\phi \sin\theta \cos\psi$
$h_{13} = -\sin\phi \cos\theta$
$h_{21} = \cos\theta \sin\psi$
$h_{22} = \cos\theta \cos\psi$
$h_{23} = \sin\theta$
$h_{31} = \sin\phi \cos\psi - \cos\phi \sin\theta \sin\psi$
$h_{32} = -\sin\phi \sin\psi - \cos\phi \sin\theta \cos\psi$
$h_{33} = \cos\phi \cos\theta$
ϕ is angle of roll, positive for right wing down
θ is angle of pitch, positive for nose up and
ψ is angle of yaw, positive for rightwards.

For $\phi = \theta = \psi = 0$, the X_p, Z_p and Y_p axes are aligned respectively with the X_e, Y_e and Z_e axes, so that Y_p then represents the vertical direction.

To obtain final screen coordinates X_s and Y_s, the processor 6 calculates

$$X_s = \frac{DX_p}{Z_p} \times \frac{NSL}{W} + \frac{NSL}{2}$$

and

$$Y_s = \frac{DY_p}{Z_p} \times \frac{NPE}{H} + \frac{NPE}{2}$$

where

D is the distance from the origin of the pilot coordinate to the screen along the Z_p axis,
NSL is the number of scan lines across the width W of the window, and
NPE is the number of pixels along a raster line equal in length to the height H of the window.

The offset quantities

$$\frac{NSL}{2} \quad \text{and} \quad \frac{NPE}{2}$$

are included so that the screen coordinates X_s, Y_s are generated having the bottom left hand corner of the window as origin as viewed by the pilot.

Since the simulated flight over three dimensional objects requires the display to show the varying appearance of, for example, buildings standing one behind the other as the aircraft flies past, the database memory 5 holds its lists of geometrical data in an order and format which enables the processor 6 to reject those surfaces which are invisible from the current position of the pilot. This facility, referred to as
5 attributing priorities to surfaces, and its method of implementation are known to those skilled in the art.

From the sets of screen coordinates for surface vertices, the processor 6 generates a list of surface start and surface end points for each raster line. This list, together with the associated surface intensity and texture data, is written into one half of a frame buffer memory 7 for surface data. The other half of the frame buffer memory 7 contains the surface data for the preceding frame which is read by a line processor 8. The
10 processor 8 reads the surface data one raster line at a time and writes intensity and texture information for each pixel into part of a line buffer memory 9. The writing operation by the line processor 8 is synchronised by pulses from a raster sync pulse generator 8a which also controls the timing of the raster line scans of the cathode ray tube 13, the synchronising pulses supplied to the processor 8 being generated at the pixel rate during each line. The line buffer memory 9 is capable of storing more than one line so that an intensity
15 modulator unit 10 can read out a complete line of pixel intensity data while the processor 8 is writing another line into the buffer memory 9.

The intensity modulator unit 10 includes logic circuitry for multiplying pixel intensity values input from the line buffer memory 9 by modulating values input by the texture data generating part of the system. The modulated intensity values are supplied by the modulator unit 10 to a digital to analog converter unit 12
20 which supplies corresponding analog intensity signals to the cathode ray tube 13.

The data base memory 5 may include colour data for each surface, and the cathode ray tube 13 may be capable of providing a colour display. Such colour data is stored in the memory 5 as a code for each surface, there being a finite number of distinguishable colours used, each being assigned a unique code. The colour data is passed through to the line buffer memory 9 with the surface intensity data but is not affected by the
25 operation of the intensity modulator unit 10, through which the colour data passes to the digital to analog converter unit 12 where red, blue and green analog signals are generated with relative intensities determined by the colour data and a combined intensity determined by the modulated intensity data supplied by the intensity modulator unit 10.

The geometrical inverse transformation matrix data signals 4 supplied by the general purpose
30 computer 2 of the visual display processing system to the transformation matrix memory 16 represents, in the present embodiment, two matrices, one for transforming screen coordinates into earth coordinates in the ground plane where $Ze=0$, and the other for transforming screen coordinates into earth coordinates in the sky plane, where $Ze=Zc$, i.e., the height of the cloud base. Which of these two matrices is supplied to a pipelined inverse perspective transformation processor 17 is determined by a texture plane number signal
35 14 supplied to the matrix memory 16 by the line buffer memory 9. The database memory 5 includes sky plane geometric feature data associated with one texture plane number, the ground plane geometric feature data being associated with the other texture plane number. The transformation matrices required to convert the screen coordinates into earth coordinates are inverse perspective matrices.

The screen coordinates are supplied to the processor 17 by a pixel counter 18 and a line counter 19.
40 These two counters are driven by synchronising pulses supplied by the raster sync pulse generator 8a. Each raster line displayed on the screen of the tube 13 contains, for example, 768 pixels. However, the height of the window is 1024 in this case, and it is arranged that only the middle 768 pixels of data from the line buffer memory 9 are displayed on the screen. This allows sufficient time for the processing carried out by the inverse perspective transformation processor 17 and subsequent stages in the generation of texture data up
45 to the intensity modulator 10 to be carried out in relation to the respective pixel intensity value input from the line buffer memory 9 to the intensity modulator unit 10. The first pixel to be displayed in any raster line is pixel number 128. Consequently, the value $Ys=128$ is supplied by the pixel counter 18 to the processor 17 at a time exactly sufficiently in advance of the output of the intensity data for pixel 128 by the line buffer memory 9 to ensure that the texture modulation applied to that intensity is the correct modulation for pixel
50 number 128. This timing relationship is ensured by the signals supplied by the raster sync pulse generator 8a to the line processor 8 and the pixel counter 18. It is also arranged that the texture plane number signal 14 and a texture pattern number signal 15 which are read out from the line buffer memory 14 and 15 are those corresponding to pixels sufficiently in advance of the pixel whose intensity is currently being read by the intensity modulator unit 10. The texture plane number signal 14 and the texture pattern number signal
55 15 are representative of the texture plane numbers and texture pattern numbers read from the database memory 5 and passed on by the processor 6 via the memory 7 and processor 8 to the line buffer memory 9 without alteration.

In addition to storing inverse transformation matrices, the transformation matrix memory 16 also stores a set of values of a constant, R, there being one value for each texture plane number. The values of R
60 are supplied to the memory 16 by the general purpose computer 2 and are calculated from:

$$R = \log_2 \frac{Ps}{DZ_o}$$

where

P_s is the screen dimension of a pixel,

D is the perpendicular distance from the pilot's eye to the screen, and

Zo is the perpendicular distance from the pilot's eye to the texture plane concerned, i.e., in the present example, to either the ground plane or the sky plane.

5 The use of the values of R will be explained hereinafter.

The pipelined inverse perspective transformation processor 17 calculates the earth coordinates Xe and Ye corresponding to the pair of screen coordinates X_s and Y_s supplied thereto by the line counter 19 and the pixel counter 18 at every eighth pixel. These values of Xe and Ye are supplied to respective linear interpolators 21 and 22 which generate pairs of Xe and Ye coordinates at the pixel rate by interpolating

10 values between those supplied by the processor 17.

In order to create a texture effect in the ground and sky planes, the intensity modulator unit 10 must modulate the pixel intensity data supplied from the line buffer memory 9 by varying the intensity values for pixels within each surface to be textured which lies within either the ground plane or the sky plane. To give a realistic appearance to the display, the present system takes into account the distance of the pilot from the

15 part of the texture plane viewed, and the angle made between that part and the line of sight. Also, unrealistic regularities due to the need to use simple repetitive texturing patterns are diminished within the system.

The system includes therefore a texture memory, represented by the three blocks 24, 25 and 28 in Figure 1, which stores intensity modulation values arranged in two dimensional arrays which are referred to

20 hereinafter as texture tiles. Each value in each such texture tile is addressable by a pair of Xe, Ye coordinate values. However, the notional area covered in the simulated ground or sky plane by a single texture tile is relatively small and must be used repeatedly to cover the larger areas of ground or sky plane displayed. Accordingly, only a predetermined number of the least significant bits of the digital values of Xe and Ye are used in addressing any point in a texture tile.

25 Each texture tile is in the form of a square area of square elements, the value of the intensity modulation held within any given element being constant. The side of each element represents a length T_e in feet in the earth coordinate system. The texture memory holds tiles having only integer values of T_e, those chosen being the powers of 2 from 2^0 to 2^{10}, so that the smallest value of T_e is 1 foot, and the largest is 1024 feet.

30 In order to limit the storage hardware required for patterns with a small value of T_e, i.e. 16 ft or less, only four basic subunits of the overall tile are stored, each consisting of a square of tile elements with a side length equivalent in the earth coordinate system to 16 feet. The overall tile is chosen to have a side length of 512 feet so that 1024 sub-units are required. However, a satisfactory effect is achieved by filling the 1024 sub-unit positions by selecting, in a fixed pseudorandom sequence, from the 32 possible choices of

35 sub-unit. The 32 choices arise from the four different orientations, 90° rotation apart, of the four basic sub-units and their mirror images.

Texture tiles with values of T_e of 32 feet and 64 feet are also 512 feet square. Texture tiles with T_e of 128, 256, 512 and 1024 feet are all 2048 feet square.

In this embodiment, the texture memory stores eight different texture patterns, each pattern being held

40 in eleven different levels of resolution, referred to hereinafter as levels of detail. The eleven different levels of detail are achieved by storing eleven texture tiles for each pattern, the tiles being those having element side lengths T_e of 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, and 1024 feet. Each level of detail is indicated by an LOD value calculated from:

$$LOD = \log_2 Te.$$

45 The texture tiles with values of LOD of 0, 1, 2, 3, 4, 5 and 6 are stored in a near texture memory block 24, and the texture tiles with values of LOD of 7, 8, 9 and 10 are stored in a far texture memory block 25. Texture tiles with values of LOD of 7 are also stored for each of the eight texture patterns in a far texture memory block 28. The LOD 7 titles of memory block 28 are used to add large scale texture features to the smaller scale texture features generated from to LOD 0 to LOD 6 tiles of memory block 24 as will be explained

50 hereinafter.

The eight different texture patterns may simulate, for example, runway surface, grass, rough water, smoothwater, sand, concrete and two types of cloud surface.

The linear interpolators 21 and 22 generate a respective pair of earth coordinates Xe and Ye for each pair of screen coordinates X_s, Y_s. The generated pair of earth coordinates thus corresponds to a pixel in the

55 display screen. The three memory blocks 24, 25 and 28 receive the earth coordinates as address signals which specify a particular element in texture tiles selected by the application of the texture pattern number signal 15 and a level of detail signal indicating the value of LOD. The texture pattern number signal 15 selects the texture pattern, and the level of detail signal selects the two texture tiles for that pattern in the memory block 24 or 25 having the integer values of LOD adjacent to the values indicated by the signal 15.

60 To explain the use of the level of detail signal, a simple example will be described in which the view presented to the pilot's eye is of a horizontal ground plane uniformly textured, at ground level, up to the horizon. The texture pattern may be grass for example. From the pilot's position, the appearance of the ground plane will be of texture in which the detail diminishes towards the horizon. This effect can be

simulated by producing the texture modulation from tiles of increasing LOD value as the earth coordinates of the pixel concerned approach the horizon. To avoid a horizontal banding effect in the displayed texture, modulation values from a pair of adjacent LOD value tiles are blended in accordance with:

$$I_B = I_N(1-F) + I_{N+1}F$$

5 where N and N+1 are the adjacent LOD values, I_N and I_{N+1} are the respective intensity values from the two tiles, I_B is the resultant blended intensity value, and F is a fraction determined by

$$F = \frac{2P_e - Te_N}{Te_{N+1} - Te_N}$$

where Te_N and Te_{N+1} are the tile element side lengths in the tiles with LOD values N and N+1 respectively, and P_e is the length of one pixel as projected onto the ground plane. The distance from the pilot's eye to the
10 centre of this projection is

$$\frac{Zp}{\cos \theta}$$

where θ is the angle between the Zp axis and the line of sight. If the actual length of a pixel at the screen is P_s, the projection P_n perpendicular to the line of sight at the distance

$$\frac{Zp}{\cos \theta}$$

15 is given by

$$P_n = \frac{P_s \, Zp \cos \theta}{D \cos \theta}$$

If α is the angle between the line of sight and the ground plane,

$$P_e = \frac{Pn}{\sin \alpha}$$

The relationship between θ and α is given by

$$\sin \alpha = \frac{Zo \cos \theta}{Zp}$$

20 where Zo is the vertical earth coordinate of the pilot's eye. Hence,

$$P_e = \frac{P_s \, Zp \, . \, Zp \cos \theta}{D \cos \theta \, . \, Zo \cos \theta}$$

$$= \frac{P_s \, Z^2p}{DZo \cos \theta}$$

Cos θ ranges from 1 at the centre of the screen to 0.878 at the corner, so that its variation is small
25 enough to allow cos θ to be treated as constant at 1. The equation used therefore to calculate P_e is:

$$P_e = \frac{P_s \, Z^2p}{DZo}$$

The level of detail signal supplied to the memory blocks 24 and 25 and to a blender 27 represents the value of $\log_2 2 P_e$. The outputs, which are two signals represent I_N and I_{N+1} from the block 24 or the block 25 are coupled through a switch 26 to the blender 27 which calculates F and produces a signal representing I_B
30 which it supplies to a mixer 31.

The value of $\log_2 2P_e$ is calculated by a level of detail processor 20 for one pixel in every eight, to correspond to the values of Xe and Ye calculated by the processor 17, which supplies a value of Zp corresponding to each pair of earth coordinates Xe and Ye calculated.

Since

$$\log_2 2P_e = 2 \log Zp + \log_2 (Ps/D) - \log_2 |Zo| + \log_2 (2),$$

the matrix memory 16 supplies a signal of value

$$R = \log_2 (P_s/D) - \log_2 |Z_o| + \log_2 (2/D)$$

to the level of detail processor 20 for each frame to be displayed.

Hence the level of detail signal generated by the processor 20 is represented by

$$\log_2 2 P_e = R + 2 \log_2 Zp$$

Since the level of detail values of the texture tiles stored in the memory blocks 24, 25 and 28 are given by

$$LOD = \log_2 Te$$

it will be seen that $2P_e$ represents a notional texture tile element side length.

A linear interpolator 23 generates a value of $\log_2 2Pe$ for each pair of Xe, Ye values applied to the memory blocks 24, 25 and 28.

Since the texture tiles selected for reading in the texture memory are addressed at the pixel rate, it will be seen that each addressed tile is sampled in the ground plane, in this example, at intervals of P_e. By selecting from memory block 24 or memory block 25 the texture tiles having LOD values equal to the integer part of $\log_e 2P_e$, say N, and equal to (N+1), it is ensured that successive tile elements are each sampled at least once but not more than twice in succession during reading out of the tile LOD value N, and successive tile elements are each sampled at least twice but not more than four times in succession during reading out of the tile with LOD value N+1. These rates of sampling ensure a sufficiently rapid spatial modulation of the displayed ground surface to avoid chequer board effects and scintillation.

When the value of $\log_2 2P_e$ is less than 7, the two texture tiles are selected from the memory block 24, and the switch 6 connects only the block 24 outputs to the blender 27. When the value of $\log_2 2P_e$ is equal to or greater than 7, the two texture tiles are selected from the memory block 25, and the switch 26 connects only the block 25 outputs to the blender 27.

The blender 27 also receives the LOD signal indicating the value of $\log_2 2P_e$, and it calculates the value of F from the relationship

$$F = 2^f - 1$$

where f is the fractional part of $\log_2 2 P_e$, i.e. $f = \log_2 2P_e - N$ since

$$F = \frac{2P_e}{Te_N} - 1$$

so that $\log_2 (F+1) = \log_2 2P_e - \log_2 Te_N$.

If the value of $\log_2 2P_e$ is between 6 and 7, then the intensity modulation values read from the tile with LOD value 6 are blended with zero intensity modulation signals. Similarly, if the value of $\log_2 2P_e$ is above 10, the modulation values are read from the tile with LOD value 10 and are blended with zero intensity modulation signals. This ensures that the texture effects fade out towards LOD values 7 and 11.

When the value of $\log_2 2P_e$ is below 7, the LOD value 7 tile for the chosen pattern is read from the memory block 28. The LOD value 7 tile is therefore oversampled, and a smoothing interpolation process is carried out by a two dimensional interpolator 29 operating on three adjacent tile element values read out from the memory block 28.

For each pair of values of Xe and Ye applied to the block 28, three values are read out as follows.

The tile elements for LOD value 7 have $Te_7 = 128$.

Let

$$\frac{Xe}{128} = X + \Delta X + \tfrac{1}{2}$$

and

$$\frac{Ye}{128} = Y + \Delta Y + \tfrac{1}{2}$$

Then $(X+\frac{1}{2}, Y+\frac{1}{2})$ are the coordinates, in whole tile elements, of the centre of the bottom left hand one of four tile elements forming a square containing the point Xe, Ye, and $(\Delta X, \Delta Y)$ are the coordinates of that point relative to that centre. The coordinates, in tile elements, of the centres of the other three elements are $(X+\frac{1}{2}, Y+1+\frac{1}{2})$, $(X+1+\frac{1}{2}, Y+1+\frac{1}{2})$, and $(X+1+\frac{1}{2}, Y+\frac{1}{2})$. If $(\Delta X+\Delta Y)<1$, then point Xe, Ye lies in the lower triangle defined by the centres $(X+\frac{1}{2}, Y+\frac{1}{2})$, $(X+\frac{1}{2}, Y+1+\frac{1}{2})$ and $(X+1+\frac{1}{2}, Y+\frac{1}{2})$. If $(\Delta X+\Delta Y)\geqslant 1$, then Xe, Ye lies in the upper triangle defined by the centres $(X+\frac{1}{2}, Y+1+\frac{1}{2})$, $(X+1+\frac{1}{2}, Y+\frac{1}{2})$ and $(X+1+\frac{1}{2}, Y+1+\frac{1}{2})$.

Let the intensity modulation values at $(X+\frac{1}{2}, Y+\frac{1}{2})$, $(X+\frac{1}{2}, Y+1+\frac{1}{2})$, $(X+1+\frac{1}{2}, Y+\frac{1}{2})$ and $(X+1+\frac{1}{2}, Y+1+\frac{1}{2})$ be respectively, A, B, C and D. Then, if $(\Delta X+\Delta Y)<1$, the three values read out are A, B and C, and if $(\Delta X+\Delta Y)\geqslant 1$, the three values read out are B, C and D. For the lower triangle the interpolated modulation value is calculated as

$$I_L = A + \Delta X(C-A) + \Delta Y(B-A),$$

and for the upper triangle the interpolated modulation value is calculated as

$$I_u = D + (1-\Delta X)(B-D) + (1-\Delta Y)(C-D)$$

The interpolator 29 implements the equations:

$$I_L = A(1-\Delta X-\Delta Y) + B\Delta Y + C\Delta X$$

and

$$I_u = D[1-(1-\Delta X)-(1-\Delta Y)] + B(1-\Delta X) + C((1-\Delta Y)]$$

X, Y, ΔX and ΔY are calculated from

$$X+\Delta X = (X_e - 64)/128$$

and

$$Y+\Delta Y = (Y_e - 64)/128$$

where X and Y are integers, and ΔX and ΔY are each less than 1.

A switch 30 connects the output of the interpolator 29 to a mixer 31 only when the memory block 24 is operative. The mixer 31 combines the blended output of the near texture memory block 24 with the interpolated output of the far texture memory block 28 in equal proportions.

When only the far texture memory block 25 is operative, the mixer 31 passes the blended output from the blender 27 to the switch 32 without change.

The switch 32 is closed for all values of the pattern number signal 15 except for one which indicates no texture. When closed, the switch 32 couples the output of the mixer 31 to the intensity modulation unit 10. The pattern number signal indicating no texture is applied when a surface which does not lie in a texture plane, i.e. in the present example does not lie in the ground plane or the sky plane, is being produced in the display.

The operations of the processor 17, and the interpolators 21, 22 and 23, will now be described in more detail.

The processor 17 receives X_s, Y_s values from the line counter 19 and the pixel counter 18, and for every eighth pixel, produces a pair of Xe, Ye values, and a Zp value.

The values of Xp and Yp corresponding to Xs, Ys are given by

$$X_p = \frac{W \cdot Z_p}{D \cdot NSL} \left(X_s - \frac{NSL}{2}\right)$$

$$Y_p = \frac{H \cdot Z_p}{D \cdot NPE} \left(Y_s - \frac{NPE}{2}\right)$$

The values of Xe, Ye and Ze, are related to the values of Xp, Zp and Yp by

$$\begin{bmatrix} X_e - X_o \\ Y_e - Y_o \\ Z_e - Z_o \end{bmatrix} = [H]^{-1} \begin{bmatrix} X_p \\ Z_p \\ Y_p \end{bmatrix} \tag{1}$$

where $[H][H]^{-1} = [I]$, the identity matrix.

However, [H] is orthogonal, so that $[H]^{-1}$ is the transpose of [H].

Hence,

$$[H]^{-1}=\begin{bmatrix} h_{11} & h_{21} & h_{31} \\ h_{12} & h_{21} & h_{31} \\ h_{13} & h_{23} & h_{33} \end{bmatrix}$$

Zo is the altitude of the aircraft, and Ze is the height above ground level of the point (Xe, Ye, Ze). Since the texture tiles in the texture memory blocks 24, 25 and 28 are addressed by the values of Xe and Ye only, they are effectively in the ground plane. Consequently, the relationships used for applying texture to the
5 displayed ground plane are obtained by putting $Z_e=0$ in equation (1). For the sky plane it is necessary to 5 treat the actual ground plane level as the sky plane, and therefore Z_o is replaced by $(-|Z_c|+|Z_o|)$, where Z_c is the cloud base height, and Z_e again put to zero, in equation (1).

Planes parallel to the ground plane but situated between the aircraft and the ground plane can also be textured if Z_o is replaced in equation (1) by Z_o-Z_B where Z_B is the height of the plane to be textured above
10 the ground plane, Ze again being put to zero. However, since the present example uses interpolation to 10 generate values of Xe, Ye and $\log_2 2P_e$, only the texturing of the ground and sky planes is carried out.
From equation (1), for the ground plane,

$$-Z_o=\frac{h_{13}W \cdot Z_p}{D \cdot NSL}\left(X_s-\frac{NSL}{2}\right)+h_{23}Z_p+\frac{h_{33}H \cdot Z_p}{D \cdot NPE}\left(Y_s-\frac{NPE}{2}\right)$$

Hence

15

$$Z_p=\frac{-Z_o}{\dfrac{h_{13}WX_s}{D \cdot NSL}+\dfrac{h_{33}HY_s}{D \cdot NPE}+h_{23}-\dfrac{h_{13}W}{2D}-\dfrac{h_{33}H}{2D}}$$

15

It can be shown that

$$\begin{bmatrix} X_t/Z_p \\ Y_t/Z_p \\ 1/Z_p \end{bmatrix}=[U]\begin{bmatrix} X_s \\ Y_s \\ 1 \end{bmatrix}$$

where $X_t=X_e-X_o$ and $Y_t=Y_e-Y_o$ and

$$U_{11}=\frac{h_{11}W}{D \cdot NSL}$$

20
$$U_{12}=\frac{h_{31}H}{D \cdot NPE}$$
20

$$U_{13}=h_{21}-\frac{h_{11}W}{2D}-\frac{h_{33}H}{2D}$$

$$U_{21}=\frac{h_{12}W}{D \cdot NSL}$$

$$U_{22}=\frac{h_{32}H}{D \cdot NPE}$$

$$U_{23}=h_{22}-\frac{h_{21}W}{2D}-\frac{h_{32}H}{2D}$$

25
$$U_{31}=\frac{-h_{13}W}{Z_o \cdot D \cdot NSL}$$
25

$$U_{32} = \frac{-h_{33}H}{Z_o \cdot D \cdot NPE}$$

and

$$U_{33} = -\frac{\left(h_{23} - \dfrac{h_{13}W}{2D} - \dfrac{h_{33}H}{2D}\right)}{Z_o}$$

The elements of [U] are constant for each frame to be displayed, and are supplied to the processor 17 from the matrix memory 16, except Xs and Ys which are supplied by the line and pixel counters 19 and 18.

5 The processor 17 calculates

$$[U]\begin{bmatrix} X_s \\ Y_s \\ 1 \end{bmatrix}$$

then the values of X_t and Y_t, and finally the values of Xe and Ye, the values of Xo and Yo being supplied by the matrix memory 16. The value of (1/Zp) is calculated from $1/Zp = U_{31} X_s + U_{32}Y_s + U_{33}$.

10 The interpolated values of Xe generated by the interpolator 21 are calculated in accordance with

$$X_{n+i} = X_n + i(X_{n+8} - X_n)/8$$

for i=0 to 7, the interpolator 21 receiving X_n and X_{n+8} as successive X_e values calculated by the processor 17.

The interpolated values of Y_e are generated in the same manner by the interpolator 22.

The use of the interpolators 21 and 22 reduces the computational load of the processor 17 by about
15 80% of the amount which would be required for calculating all values of Xe and Ye using the processor 17 alone.

For the sky plane, Z_o is replaced by $(-|Z_c| + |Z_o|)$ in the equation for Zp, and hence in U_{31}, U_{32} and U_{33}. Consequently the use of interpolation causes an error where the values of X_s and Y_s change from defining a point in the ground plane to a point in the sky plane, or vice versa, which does not coincide with
20 the end of an interpolation interval. However, as such changes always take place at the horizon, the texture modulation is zero, and the error cannot be seen. It is arranged that texture, in the present example, fades out within 8 pixels of the horizon. This type of error is the reason why only the ground and sky planes are textured when the interpolators 21 and 22 are used.

The processor 17 computes Xe, Ye for every eighth pixel along a raster line starting at $Y_s = T$ where T is
25 the delay between the input of the processor 17 and the output of the mixer 31.

The transformation matrix memory 16 comprises an arrangement of RAMs. The elements of [U] are loaded into these RAMs by the general purpose computer 2 during a frame update sequence. There is one U matrix for each texture plane. The correct U matrix is selected by the texture plane number signal 14. A fresh value of R is also supplied to the memory 16 by the computer 2 during each frame update sequence.
30 The level of detail processor 20 generates the value of $\log_2 2Pe$ as an output only for the range $0 \leqslant \log_2 2P_e < 11$. If $\log_2 2P_c$ is calculated to be less than zero, then the output value generated is zero. If $\log_2 2P_c$ is equal to or greater than 11, output from the texture memory blocks 24, 25 and 28 is set to zero so that no modulation of the intensity values from the line buffer memory 9 results.

The linear interpolator 23 operates in the same way as the interpolators 21 and 22.
35 The three linear interpolators 21, 22 and 23 can be implemented as two circuit cards each containing two 16 bit interpolator circuits which are clocked at half the pixel rate, e.g. 20 Megahertz. Each 16 bit interpolator circuit generates simultaneous values for the odd and even pixels. The even pixel output is passed through an additional register clocked by the opposite phase pixel rate to provide one pixel of delay relative to the odd pixel output.
40 The memory blocks 24 and 25 are then also implemented as two circuit cards, one for even pixels and the other for odd pixels, with each card including memory for texture tiles of the eight patterns at all values of LOD from 0 to 10. Tile elements are stored as 5 bit logarithmic modulation values representing a modulation range of $\frac{1}{2}$ to <2. Zero modulation has a value of 1 which, in logarithmic form, is zero.

The memory block 28 is, in this example, implemented as two circuit cards, one for even pixel output
45 and the other for odd pixel output.

The outputs from the blender 27 and the interpolator 29 are representative of, respectively, $\log_2 I_B$ and $\log_2 I_1$ where I_B is the blended intensity modulation value, and I_t is the interpolated intensity modulation value. The mixer 31 produces an output representative of

$$\log_2 I_T = \log_2\left[\frac{I_B + I_I}{2}\right]$$

where I_T is the final intensity modulation value.

Fig. 2 shows an implementation of the memory blocks 24 and 25 with the switch 26 and blender 27. In the circuit of Fig. 2 the values of Xe and Ye supplied to a latch circuit 33 which passes the five bits of Xe corresponding to values 2^4 to 2^8 feet and the five bits of Ye also corresponding to values 2^4 to 2^8 feet to a subtile decode circuit 34 which decodes the ten bits to one of 1024 addresses of subtile codes, the subtile codes at these addresses being a random sequence formed from thirty two codes each representing one of the thirty two possible subtile arrangements created by eight dispositions of four subtiles. Each of the thirty two subtile codes is represented by a five bit number in which the two most significant bits define the basic one of four subtitles and the three least significant bits define a respective one of the eight possible dispositions.

The three least significant bits from the subtile decode circuit 34 are supplied to an orientating circuit 35 which is also supplied the four bits of Xe and the four bits of Ye corresponding to the values 2^3 feet down to 2^0 feet. In dependence upon the value of the three bit signal from the subtile decode circuit 33, the orientating circuit 35 transforms the low order bits for Xe and Ye into values for subtile coordinates TX and TY for addressing points within a subtile. The operation is summarised in the following table in which X represents the low order Xe bits and Y represents the low order Ye bits.

Orientation code	TX	TY
0	X	Y
1	Y	X
2	$\overline{X}$	Y
3	$\overline{Y}$	X
4	X	$\overline{Y}$
5	Y	$\overline{X}$
6	$\overline{X}$	$\overline{Y}$
7	$\overline{Y}$	$\overline{X}$

The subtile decode circuit 34 may be a PROM, and the orientating circuit 35 may be a suitable logic gate and inverter circuit.

The subtile code and subtile coordinates thus generated are used only for tiles at levels 0, 1, 2, 3 and 4. The values of Xe and Ye are passed through by the latch 33 for use at levels 5 to 11.

The outputs of the subtile decode circuit 34 and the orientating circuit 35 are supplied to an address generator 36 together with the values of Xe and Ye, the LOD signal and the pattern number signal. The address generator 32 generates two thirteen bit addresses which it supplies respectively to a left RAM 37 and a right RAM 38. The three high order bits are obtained by decoding the pattern number signal and identifies which one of the eight possible patterns is selected. All levels 0 to 10 are stored for each pattern in the RAMs 37 and 38, each 1K word block in each RAM containing at least part of the tile for each level of one pattern. One bit, TS0, from the subtile decode circuit 34 or one bit from Xe is used to determine which RAM is selected for a particular level of detail, a pair of adjacent levels being selected for each value of the LOD signal with one of the levels being selected from the left RAM 37 and the other level from the right RAM 38. The value of the integer part of the LOD signal is decoded to form part of the addresses supplied to the RAM 37 and 38. For LOD values 0, 1, 2, 3 and 4, each of the RAMs 37 and 38 contains two subtiles. If the four basic subtiles are identified as 00, 01, 10 and 11 by the output bits TS1 and TS0 from the subtile decode circuit 34, then if for level 0 the subtiles 00 and 10 are held in the left RAM 37 and subtiles 01 and 11 are held in the right RAM 38, the subtiles 01 and 11 for level 1 are held in RAM 38, the subtiles 00 and 10 are held in RAM 37 for level 2 and the subtiles 01 and 11 are held in RAM 38 for level 2, and so on up to level 4. This arrangement ensures that corresponding subtiles are selected for the adjacent levels up to level 4. A table of address bits for the RAMs 37 and 38 for one pattern is shown below.

Blended Tile Array Address Map

Address	Contents		9	8	7	6	5	4	3	2	1	0	Left/Right Ram Select
							Ram Address Bits						
0 to 511	4 near texture subtiles at level	0	0	TY0	TX0	TY1	TX1	TY2	TX2	TY3	TX3	TS1	TS0
512 to 639	4 near texture subtiles at level	1	1	0	0	TY1	TX1	TY2	TX2	TY3	TX3	TS1	$\overline{TS0}$
640 to 671	4 near texture subtiles at level	2	1	0	1	0	0	TY2	TX2	TY3	TX3	TS1	TS0
672 to 679	4 near texture subtiles at level	3	1	0	1	0	1	0	0	TY3	TX3	TS1	$\overline{TS0}$
680 to 683	4 near texture subtiles at level	4	1	0	1	0	1	0	1	0	TS0	TS1	TS0/X8*
684 to 685	far texture tile at level	10	1	0	1	0	1	0	1	0	0	Y10	X10
686 to 687	Zero		1	0	1	0	1	0	1	1	1	—	—
688 to 695	far texture tile at level	9	1	0	1	0	1	1	0	Y9	X9	Y10	$\overline{X10}$
696 to 703	Zero		1	0	1	0	1	1	1	—	—	—	—
704 to 735	far texture tile at level	8	1	0	1	1	0	Y8	X8	Y9	X9	Y10	X10
736 to 767	near texture tile at level	6	1	0	1	1	1	Y6	X6	Y7	X7	Y8	X8
768 to 895	near texture tile at level	5	1	1	0	Y5	X5	Y6	X6	Y7	X7	Y8	$\overline{X8}$
896 to 1023	far texture tile at level	7	1	1	1	Y7	X7	Y8	X8	Y9	X9	Y10	$\overline{X10}$

* For selecting left/right at level 4 use X8 if level N and TS0 if level N+1. X0 to X10 have values of 2^0 ft to 2^{10} ft respectively. Similarly for Y, TX and TY.

As an example, if the value of the LOD signal is 2.5, the level 2 is selected in one RAM and the level 3 is selected in the other RAM, i.e. bits 9 down to 5 are 10100 in the address generated for one RAM, and bits 9 down to 3 are 1010100 in the address generated for the other RAM. Which RAM supplies the address for level 2 and which the address for level 3 is determined by the value of TS0. The value of TS1 determines

5   which level 2 or 3 subtile of the two in each RAM is to be addressed. The element within the subtile is   5
addressed by the values of TY2, TX2, TY3 and TX3 in level 2, and the values of TY3 and TX3 in level 3. TY0 to TY3 are the bits 0 to 3 of TY, and TX0 to TX3 are the bits 0 to 3 of TX. For levels 5 and above, one complete tile is stored in each RAM. Thus if a level 5 and a level 6 tile are to be selected, the level 5 tile will be addressed by 1, 1, 0, Y5, X5, Y6, X6, Y7, X7, Y8, and the level 6 tile will be addressed by 1, 0, 1, 1, 1, Y6, X6,

10   X7, Y8. The value of X8 determines which RAM provides the level 5 tile and which the level 6 tile. For levels   10
7 to 10, the value of X10 or $\overline{X10}$ determines which RAM is addressed for a particular level, the other RAM automatically being addressed for the adjacent higher level. For LOD values between 6 and 7 and between 10 and 11, one RAM is addressed with 1, 1, 1, YY, X7, Y8, X8, Y9, X9, Y10 or 1, 0, 1, 0, 1, 0, 1, 1, 0, Y10, and the other RAM is addressed with 1, 0, 1, 0, 1, 1, 1, -, -, -, or 1, 0, 1, 0, 1, 0, 1, 1, 1, -, both of which are addresses for

15   zero modulation values.   15
The RAM selecting bit TS0, X8 or X10 is also supplied to two multiplexer circuits 39 and 40 which, in dependence upon the value of the RAM selecting bit, direct the output of the RAM providing the N level to a N level input of the blender 27, and the output of the RAM providing the N+1 level to an N+1 level input of the blender 27.

20   The bits of Xe and Ye used to address a subtile of level n are the bits with the values 2^3 feet down to 2^n 20
feet, where n=0, 1, 2 or 3. When a subtile of level 4 is to be addressed, there is only one element per subtile, so that only TS0 and TS1 are needed to specify the element completely.
When 7 LOD 11, the RAMs 37 and 38 are addressed directly from Xe and Ye with the bits having the values 2^{10} feet down to 2^1 feet.

25   It will be seen that the ten least significant bits of the RAM address word define the point selected with   25
the tiles for one pattern.
The database memory 5 stores, for each surface defined therein, a control word of four bits which encode the plane number and the pattern number. This control word is decoded at the line buffer memory 9 into the three bit pattern number code which forms the three higher bits of the RAM address, and a one bit

30   plane number, the two planes in this example being the ground plane and the sky plane. Two of the control   30
word values are not used, one specifies a default for non-textured surfaces, one specifies a non-textured ground plane, and another one specifies a non-texture sky. The remaining twelve specify textured ground or sky planes.
To avoid interruption of the operation of the linear interpolators 21, 22 and 23 at boundaries between

35   the ground or sky plane and non-textured surfaces lying in other planes, it is arranged that the control word   35
for default for non-textured surfaces is associated with non-textured surfaces not lying in the ground or sky plane, and that the occurrence of this control word at the line buffer memory 9 disables the plane number of the non-ground plane, non-sky plane surface and preserves the plane number of the background, which is either the ground plane or the sky plane. The effect of this operation is not seen, since the switch 32

40   prevents the output of the mixer 31 from reaching the intensity modulation unit 10 except when a ground   40
plane or sky plane surface is to be textured.
The memory block 28 includes three RAMs, each holding a copy of the tile array for level 7 of each pattern only. Three tile elements, one from each RAM, are addressed simultaneously. Two of these elements supply the values B and C, and the other supplies A or D. The address word is formed from the Xe

45   and Ye bits with values 2^{10} feet down to 2^7 feet. The fractional parts ΔX and ΔY are formed from the bits with   45
values 2^6 feet down to 2^{-1} feet. The values of $(1-\Delta X)$ and $(1-\Delta Y)$ are generated approximately by a logic inversion. The interpolation function is carried out by using five PROMs.
The following table gives the sizes of the tile elements and numbers of elements for LOD levels 0 to 10.

Texture Tile Parameters

LOD (Level N)	Tile Element Dimension FT	Near Texture Tiles (512'×512')			Far Texture Tiles (2048'×2048')		
		Size of Stored Array			Size of Stored Array		
		Elements	FT		Elements	FT	
0	1	4×16×16	4×16×16		Interpolate level 7		
1	2	4×8×8	"	Blend with level N+1			
2	4	4×4×4	"				
3	8	4×2×2	"				
4	16	4×1×1	"				
5	32	16×16	512×512				
6	64	8×8	"	*			
7	128	No near texture			16×16	2048×2048	Blend with level N+1
8	256				8×8	"	
9	512				4×4	"	
10	1024				2×2	"	
							*

* At levels 6 and 10 blend with zero modulation value.

Although the example of visual display generating apparatus described hereinbefore with reference to the drawings is intended to be used in a flight simulation system, it will be apparent that similar apparatus within the scope of the invention may be adapted for use in a simulation system for a ground based vehicle such as a tank, or for use in a simulation system for a helicopter or an amphibious craft.

CLAIMS

1. Apparatus for generating a visual display, comprising first memory means storing geometrical surface data and associated surface appearance data including surface intensity data, the geometrical surface data including coordinates for points characteristic of defined surfaces, first processing means arranged to select from the data stored in the first memory means geometrical surface data and the associated surface appearance data for creating a display of a restricted two-dimensional perspective view of a region defined by observation point and attitude data supplied to the first processing means, the first processing means including input means for receiving variable observation point and attitude data, display means coupled to the first processing means for displaying the said restricted perspective view, second memory means storing surface detail data representing at least one planar pattern, the surface detail data comprising a plurality of intensity modulation values each stored at an address defined by a pair of pattern plane coordinates, second processing means coupled to the input means to receive observation point and attitude data and to means for generating and supplying thereto pairs of display coordinates corresponding to points in the visual display, the second processing means being such as to generate for each pair of display coordinates supplied thereto a corresponding pair of pattern plane coordinates substantially determined by an inverse perspective projection from the observation point to a plane defined in the coordinate system of the said points characteristic of defined surfaces, addressing means coupling the second processing means to the second memory means so as to address the second memory means with the pairs of pattern plane coordinates, and intensity modulation means so coupling the second memory means to the display means as to cause the intensity data selected by the first processing means for a displayed point to be modulated by an intensity modulation value obtained from the second memory means for the same displayed point.

2. Apparatus according to claim 1, wherein the geometrical surface data stored in the first memory means includes plane identifying data associating each of one or more defined surfaces with a plane definable within the coordinate system of the said points characteristic of defined surfaces, the first

processing means including means for supplying the said plane identifying data to the second processing means and the second processing means being adapted to utilize a perspective transformation associated with the plane identifying data.

3. Apparatus according to claim 1 or 2, wherein the surface detail data stored in the second memory means represents a plurality of identifiable planar patterns, the surface appearance data stored in the first memory means includes surface detail pattern identifying data, the first processing means includes means for supplying the said surface detail pattern identifying data to the second memory means, and the second memory means is adapted to output the intensity modulation values associated with the said pairs of pattern plane coordinates in the pattern identified by the said surface detail pattern identifying data supplied thereto by the first processing means.

4. Apparatus according to any preceding claim, wherein the surface detail data stored in the second memory means represents at least one planar pattern at a plurality of levels of detail, the second processing means is such as to generate a level of detail signal representative of a measure of minimum spacing in the pattern plane at which a difference in appearance can be represented by the display means, and to supply the level of detail signal to the second memory means, the addressing means is such as to address the second memory means with the pairs of pattern plane coordinates at one or more levels of detail determined by the level of detail signal, and the intensity modulation means includes means for combining two or more intensity modulation values read out from two or more levels of detail in the second memory means in response to a respective pair of pattern plane coordinates so as to produce the said intensity modulation value which modulates the selected intensity data.

5. Apparatus according to claim 4, wherein the addressing means is arranged to address the second memory means at pairs of adjacent levels of detail and the intensity modulation means is such as to blend the values from the said adjacent levels so as to prevent banding effects at the display means.

6. Apparatus according to claim 4 or 5, wherein the addressing means is such as to transform the pairs of pattern plane coordinates in response to predetermined values of the level of detail signal so as to use the said pair of pattern plane coordinates to address a predetermined restricted area of the pattern plane relative to a plurality of different addressing schemes, and for the predetermined values of the level of detail signal the second memory means stores the respective planar pattern in the form of one or more sub-units of the pattern.

7. Apparatus according to any preceding claim, wherein the second processing means includes means for generating successive pairs of pattern plane coordinates by interpolation.

8. Apparatus according to any one of claims 4, 5 and 6, wherein the second processing means includes means for generating successive values of the level of detail signal by interpolation.

9. Apparatus according to any preceding claim, wherein the first processing means includes a general purpose computer adapted to supply perspective transformation data for use by the first processing means and inverse perspective transformation data for use by the second processing means.

10. Apparatus according to claims 2 and 9, wherein the second processing means includes transformation data memory means for storing inverse transformation data supplied thereto by the general purpose computer and is adapted to select such stored data in dependence upon plane identifying data supplied thereto by the first processing means.

11. Apparatus for generating a visual display, substantially as described hereinbefore with reference to the accompanying drawings.

Superseded Claim 10
New or Amended Claims:—

10. Apparatus according to claims 2 and 9, wherein the second processing means includes transformation data memory means for storing inverse transformation data supplied thereto by the general purpose computer for a plurality of planes and is adapted to select such stored data in dependence upon plane identifying data supplied thereto by the first processing means.

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